Managing Vegetation to Increase Flow in the Colorado River Basin

Alden R. Hibbert

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Abstract

Water yield from forest and rangelands can be augmented by managing vegetation and snow to reduce evapotranspiration. Some arbitrary goals to increase water yield were chosen to illustrate the potential for increasing water yield, and treatments were hypothesized to get these increases.

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Alden R. Hibbert
Principal Hydrologist

Rocky Mountain Forest and Range Experiment Station[2]

[1]This report summarizes a much more detailed paper prepared in cooperation with the Pacific Southwest Interagency Committee. The main paper, "Vegetation management for water yield improvement in the Colorado River Basin," is available by accession number PB300379/AS from National Technical Information Service, U.S. Department of Commerce, 5825 Port Royal Road, Springfield, Va. 22161.

[2]Central headquarters at Fort Collins in cooperation with Colorado State University; author is at the Station's Research Work Unit at Tempe, in cooperation with Arizona State University.

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Management Implications

The combined surface and ground water supplies in the Colorado River Basin are generally adequate for current needs. However, growing demands and use of water in the Colorado River Basin could result in a widespread water shortage as early as 1995.[3] Local shortages exist already. One method of augmenting the water supply is management of forest and brush lands to increase streamflow.

Theoretically, the surface water supply in the Colorado River Basin could be increased by as much as one-third (6 million acre-feet annually) if vegetation and snow on 16% (26 million acres) of the basin were manipulated solely to increase water yield. However, other forest resources, economics, and social and environmental concerns must also be considered, which tend to greatly reduce both treatment area and effectiveness.

Water yield increases are greatest where large reductions can be made in water transpired by plants and/or evaporated from snow. Clearcutting and type conversion usually increase water yield the most. These practices may be appropriate in several vegetation types, such as chaparral and mountain brushlands, where the commercial value of the vegetation is low. However, where clearcuts and type conversions are not acceptable management practices, the potential for increasing water yield is less, although it may still be substantial in many cases.

[3] *U. S. Department of Interior, Bureau of Reclamation. Executive Summary of critical water problems facing the 11 western states. Westwide Study. 85 p.*

Where much snow falls in windswept, treeless areas, evaporation of blowing snow can be reduced by trapping snow in large drifts behind snow fences, where it more effectively contributes to streamflow. Opportunities exist to increase water yield by this technique on selected sites in alpine, high elevation sagebrush, and mountain grassland areas. However, the high cost of snow fences and their visual impact on the open landscape must be taken into account.

In the examples used in this report, Upper Basin yield could be increased by 500,000 acre-feet per year, or 3.5%, by treating up to 22% of each vegetation type, except aspen, in which 40% would be treated. About one-half of the increase would come from the subalpine forests, including Douglas-fir. In the Lower Basin, more extensive treatments would be necessary to get an additional 250,000 acre-feet annually, an 8% increase in water yield. About 92% of the total increase would be generated by treatment of about 20% of the chaparral and 33% of the ponderosa pine.

While information on cost of producing extra water is incomplete, it is believed that the least expensive water would come from commercial forests, where timber yields would pay for part of the treatment costs. Water would be more expensive from type conversions, because most of the treatment costs would be levied against water production. However, most of the water is expected to cost less than imported water, and some of the water from commercial forests would supplement and be in the price range of water produced by weather modification.

Introduction

Setting a realistic goal for increasing water yield through vegetation management requires a careful balance between needs, costs, and resource capabilities. The water user wants to know how much water can be produced and the cost. The land manager, however, must decide on resource allocations based on complex interactions with various segments of the public, and he must adhere to management guidelines stipulated by Congress.[4] Both the water user and the land manager need to consider how the cost of additional water production compares with the cost of achieving more efficient delivery and application of water already in the system. Further, the future demand for water and other forest resources and uses can change, and thus affect priorities and availability of treatable areas. Therefore, no attempt was made in this report to specify the amount of additional water that could be produced by management of vegetation and snow, except to show how arbitrary amounts might be generated by applying hypothetical treatments to selected portions of the Upper and Lower Basins. The examples chosen were not meant to suggest an attainable level of water yield increase, but rather to show the kinds of treatments and how much area might be affected, given an augmentation goal.

Public acceptance of water yield improvement practices will partly depend on how people view the need for more water (basically an economic issue), and on how they perceive the impacts of water improvement practices on the forest environment, including the less tangible resources such as wildlife and scenic beauty.

For water yield improvement projects to become fully effective would require several decades in commercial forests, where the rotation age of tree harvest may vary up to 120 years or more. Type conversion in brushlands would become operational much faster. Pilot applications help to bridge the gap between small watershed experimentation and large-scale action programs. An operational scale study of multiresource management in ponderosa pine is being conducted by the USDA Forest Service on the Beaver Creek Woods Canyon experimental watershed in central Arizona. A similar study is being initiated in the chaparral, and others are being considered for other vegetation types in both Upper and Lower Basins.

[4]*Provisions of the Forest and Rangeland Resources Planning Act of 1974 (88 Stat. 476, et seq.), as amended by the National Forest Management Act of 1976 (90 Stat. 2949, et seq.) (16 U.S.C.1601-1614).*

Water Resources in the Colorado River Basin

The Colorado River drains nearly 250,000 square miles, or 160 million acres in seven western states before entering the Gulf of California in Mexico. The basin includes virtually all of Arizona and portions of New Mexico, Colorado, Wyoming, Utah, Nevada, and California (fig. 1). The drainage area is divided into Upper and Lower Basins at Lee Ferry, about 10 miles south of the Utah-Arizona border. The Upper Basin contains about 70 million acres, and the Lower Basin contains 90 million acres. Lee Ferry is the official Compact point for apportioning flow from the Upper Basin for use by states within both the Upper and Lower Basins.

Precipitation averages 15.7 inches annually in the Upper Basin, where it concentrates in the mountains (fig. 1); the Lower Basin is drier, with 13 inches (fig. 1). The proportion of precipitation yielded as streamflow is more than five times greater in the Upper Basin (16% or 2.5 inches) than in the Lower Basin (3% or 0.4 inch). Overall, three-fourths of the water yield comes from less than 15% of the land area.

Precipitation and streamflow vary greatly from year to year. Annual yields from the Upper Basin at Lee Ferry have varied from 37% to 163% of the 83-year mean flow of 14.7 million acre-feet (fig. 2). Yield fluctuates even more in the Lower Basin. Seasonally, flow is concentrated in a few months out of each year when the snow melts.

Storage facilities are necessary to fully utilize water resources, especially additional water from vegetation management, because the increases are largest in wet years when flows already are high. Major reservoirs on the Colorado River and its tributaries provide usable storage for about 32 million acre-feet in each of the Upper and Lower Basins. When full, these reservoirs hold nearly four times the annual water yield of the entire Colorado River drainage area. In some headwater areas, however, seasonal deficiencies in water supply may develop because of inadequate storage facilities.

Water yield from the Upper Basin averaged 16.8 million acre-feet for the 26 years of records prior to the 1922 Colorado River Compact, which apportioned 7.5 million acre-feet for consumptive uses in the Upper Basin, and obligated the Upper Basin to release no less than 75 million acre-feet to the Lower Basin every 10 years (7.5 million acre-feet per year). A later commitment guaranteed delivery of 1.5 million acre-feet per year to Mexico, with the stipulation that both Upper and Lower Basins are to share equally in meeting this obligation if there

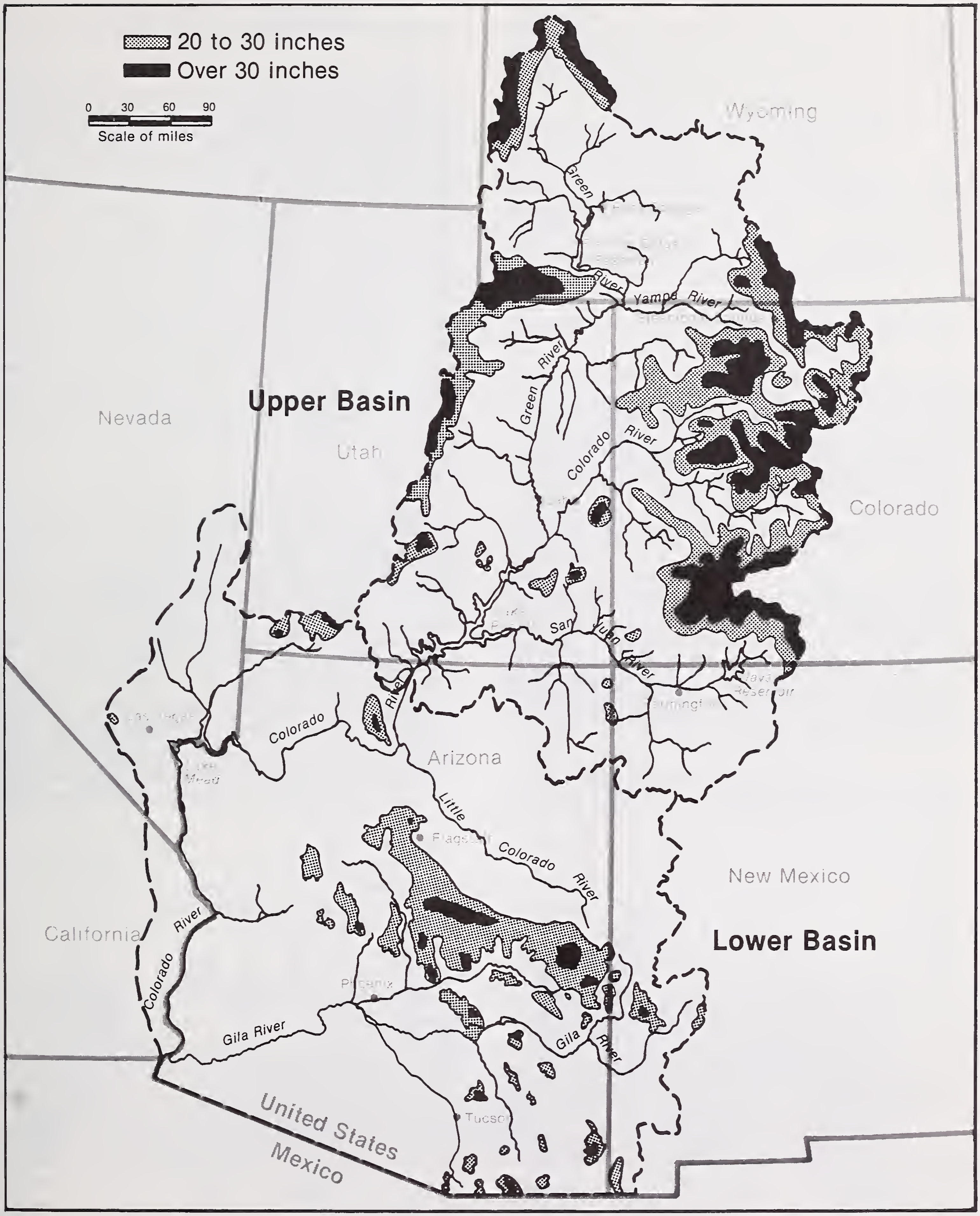

Figure 1.—Precipitation distribution is shown for the Upper and Lower Basins of the Colorado River which occupy portions of seven western states.

is insufficient water surplus to the apportionments. Together, these commitments totaled 16.5 million acre-feet, a not unrealistic demand on Upper Basin water yield based on records prior to 1922. Since then, however, undepleted flow at Lee Ferry has averaged less than 14 million acre-feet, which many believe is about all that can be expected over the long run. Long-term streamflow records, reconstructed from tree rings by Stockton and Jacoby (1976), indicate that for the past 450 years, flow at Lee Ferry has averaged 13.5 million acre-feet. Their analysis showed that only one other period, the early 1600's, was as wet as the first 30 years of this century.

While present mainstream water uses of about 12 million acre-feet per year in both Upper and Lower Basins are below the long-term trend in average annual water supply, this supply is less than the apportionments and the Mexican delivery obligation. Future water needs for development of the Basin's energy resources and other uses have been forecast to exceed supplies by about the year 2000.[5]

Water yield within Lower Basin watersheds is about 3.1 million acre-feet per year, much of which is used in Arizona. Additional large amounts of water are pumped from ground water to supply agriculture and municipal-industrial needs. Ground water overdraft in the Lower Basin averages nearly 2.5 million acre-feet per year. To sustain the current use rate will require continued overdraft of ground water, even with completion of the Central Arizona Project, unless the supply can be augmented.

[5]*USDI, Water for Energy Management Team. Report on water for energy in the Upper Colorado River Basin. 1974. 71 p.*

Increasing Water Yield by Management of Vegetation and Snow

Of the average 190 million acre-feet (14.2 inches) of rain and snow that fall each year on the Colorado River Basin, more than 90% of it evaporates. With such large amounts of water being returned to the atmosphere, even a slight reduction in this loss would leave substantially more water for streamflow. If, for example, evapotranspiration over the entire Colorado River Basin could be reduced by only 1%, the surface water supply would increase on the average by 1.75 million acre-feet annually. However, the opportunity to significantly reduce evapotranspiration by management of vegetation and snow is limited to certain types of cover. Only about 16% (26 million acres) of the basin is vegetated well enough or has sufficient snow to be suitable for water yield improvement measures.

Vegetation is controlled largely by climate. Areas of low rainfall dominate the Lower Basin, where vegetation is sparse and drought resistant. Precipitation generally increases with elevation and latitude, until at mid to upper elevations, brush, pinyon-juniper, and associated types are replaced by forests. Eventually, the forests give way to the cold, harsh climate of the alpine zone, where only low-growing forms of vegetation survive. Precipitation varies from less than 5 inches annually in the deserts to more than 50 inches in the wettest mountain areas. Potential evapotranspiration tends to be inversely related to precipitation, because energy for evaporation declines with increasing elevation, latitude, and cloudiness.

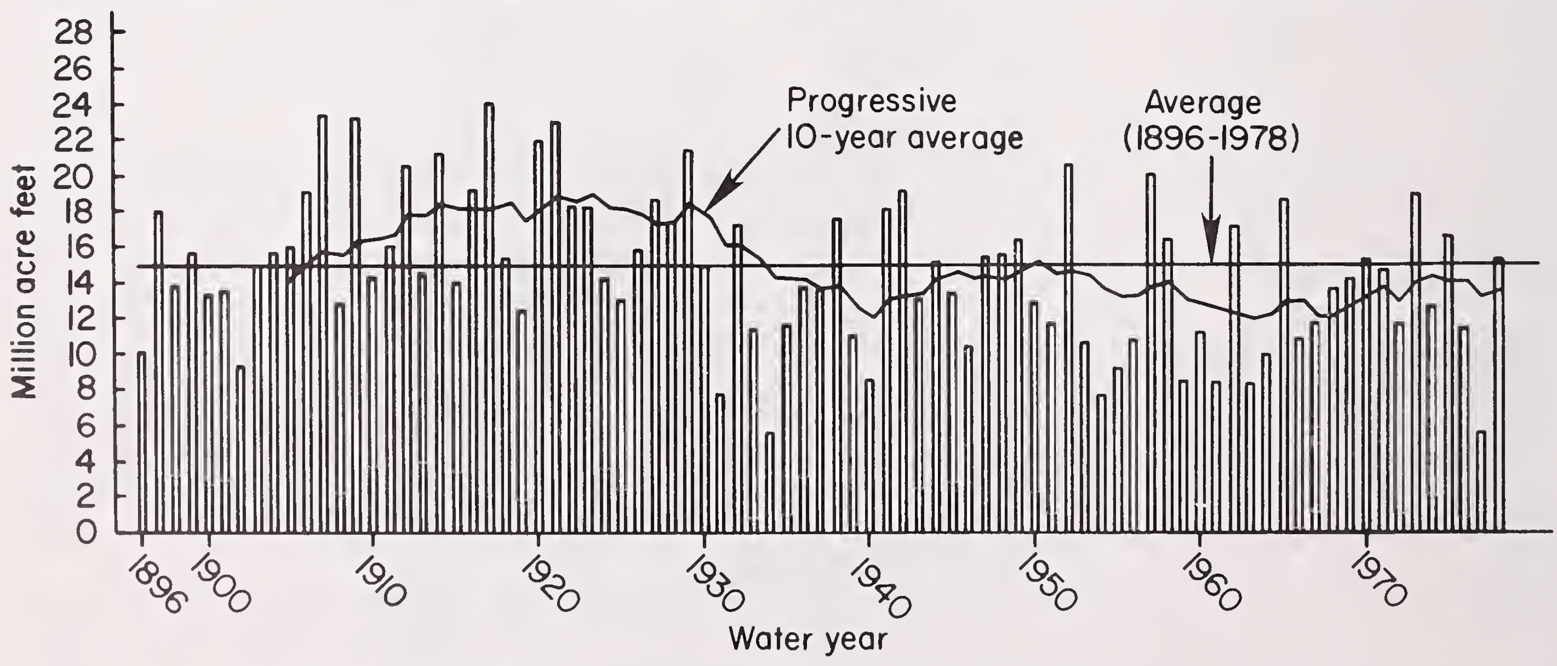

Figure 2.—Annual undepleted (virgin) flows of the Colorado River at Lee Ferry, Arizona, 1896-1978.

Water yield, therefore, increases rapidly with precipitation, from near zero in the deserts to as much as 40 inches in alpine areas.

Water yield improvement, as it pertains to forest and rangelands in the Colorado River Basin, is based on the premise that streamflow and/or ground water are increased by an amount equal to the net reduction in evapotranspiration. Little opportunity exists to reduce transpiration where precipitation is less than about 18 inches (fig. 3) and is exceeded by potential evapotranspiration (warm, dry portions in fig. 3), because rains do not penetrate far into the soil, and one cover type is about as efficient as another in using available water. At the other extreme (the cold, wet climate), the opportunity to decrease transpiration is limited because water use by plants already is low, and further reductions are difficult to obtain. The greatest opportunity exists where precipitation exceeds 18 inches and potential evapotranspiration (determined by the Thornthwaite method) exceeds 15 inches. This kind of climate promotes vigorous growth of vegetation capable of using large amounts of water. Modifying cover under these conditions can substantially increase water yield. Riparian vegetation represents a special situation because of water availability to plants in addition to natural precipitation in areas where the potential for evapotranspiration is often quite high.

The best opportunity to increase water yield by snow management is in cold climates where blowing snow can be concentrated in forest openings or trapped in large drifts to reduce evaporation.

Vegetation can be managed in several ways to reduce evapotranspiration:

1. Reduce stand density by various practices to reduce transpiration and interception.
2. Convert from one cover type to another that uses less water (type conversion).
3. Create openings in forest cover to reduce transpiration and to redistribute snow, concentrating it to reduce evaporation and increase snowmelt contribution to streamflow.
4. Establish trees or large shrubs in windswept, treeless areas to pile snow in large drifts, thereby reducing evaporation.

Snow management can save considerable water (Tabler 1973). As snow particles are blown along by wind in open terrain, they undergo significant evaporation (sublimation) loss and may completely sublimate after being transported a few thousand feet. By trapping snow behind natural or artificial barriers, such as snow fences, evaporation is reduced and snowmelt water is concentrated to enhance its delivery to the stream. In the forest, specific management practices can be used to promote redistribution of snow by wind from uncut areas of the forest to specially designed openings. When concentrated in this way, more of the snow melts and contributes to streamflow than if snow is uniformly distributed over the entire forested area.

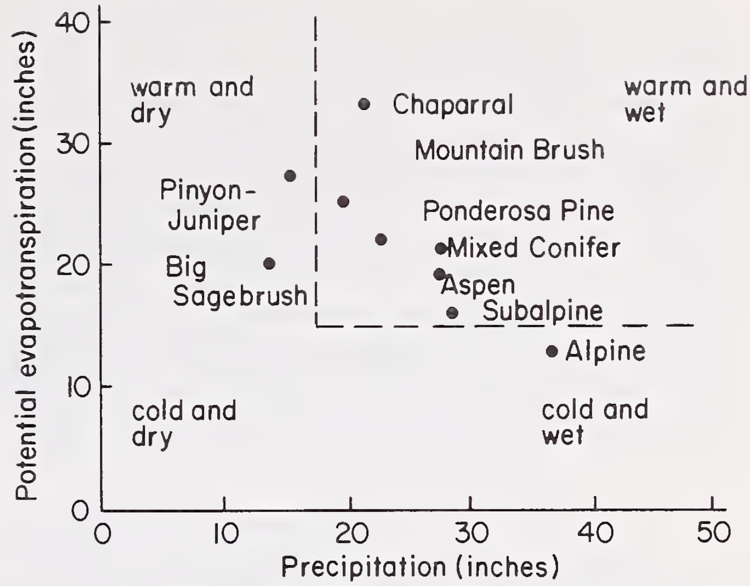

Figure 3.—General relationship of vegetation to potential evapotranspiration (PE) (Thornthwaite and Mather 1957) and precipitation (P) in the Colorado River Basin. The ranges in PE and P are broader than indicated by the average values plotted for each vegetation type. Aspen, for example, overlaps the area between ponderosa pine and subalpine. The dashed lines represent approximate marginal conditions for improving water yield by manipulation of vegetation; the potential is greater in the direction of warm and wet climate.

The method of treatment will vary with vegetation type, climate, soils, topography, and with social, economic, and environmental considerations. Clearcutting and type conversion usually produce maximum increases in water yield compared to thinning and patch cutting. An exception may be in areas of heavy snowfall, where patch cuts or strip cuts of appropriate size and spacing appear more efficient then large clearcuts (Leaf 1975).

Thinning, the uniform reduction of forest cover, is probably the least effective method of increasing water yield in the Colorado River Basin, where summer moisture usually falls short of plant water demands. As soil water depletes during the growing season, plants compete for available moisture. In this situation, plants that remain after thinning are capable of using additional water if it becomes available by removal of nearby plants (fig. 4). As a general rule, uniform thinning of forest and brush stands in the Rocky Mountains and Southwest must remove about 50% of the crown cover before water yield appreciably increases. For this reason, silvicultural systems that use shelterwood or indi-

vidual tree selection methods of harvest are not as water productive as harvest systems that create openings in the forest cover.

Type conversion, the permanent replacement of one cover type with another (fig. 5), may be appropriate in several vegetation types. In addition to water, other benefits, such as increased forage and reduced fire hazard, may accrue. However, other resources, such as timber, food and cover for wildlife, scenic values of the landscape, and soil stability, require consideration in resource management decisions. Such considerations will bear on how much of the water yield potential can actually be achieved.

Figure 5.—Type conversion of brush to grass (foreground) increases water and forage yields, improves wildlife habitat by increasing edge and species diversity, and reduces fire hazard by breaking up large, continuous blocks of dense cover.

Potential Increases by Vegetation Types

Eleven cover types were delineated based on differences in water response to treatment. These cover types are alpine, mountain grasslands, subalpine, mixed conifer, aspen, ponderosa pine, mountain brush, chaparral, big sagebrush, pinyon-juniper, and upstream riparian. Together these cover types occupy some 76 million acres in the Colorado River Basin, nearly one-half of the total area. However, about 50 million acres are classified as sagebrush and pinyon-juniper which have little or no potential, except on exceptional sites. Thus the focus is on about 26 million acres or 16% of the entire basin. Phreatophytes along downstream portions of the major rivers were not included in this study.

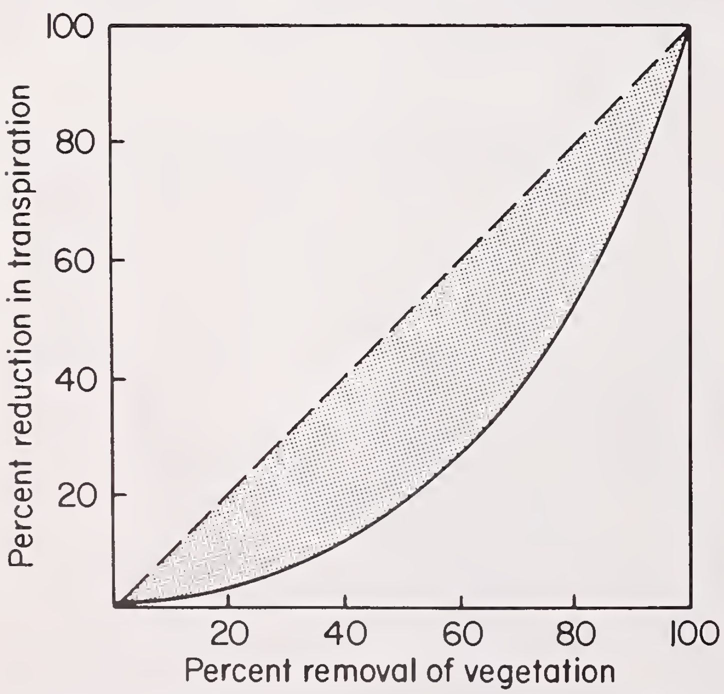

Figure 4.—Hypothetical reduction in transpiration as a function of uniform removal (thinning) of trees and shrubs under conditions that vary from unlimited soil water availability to plants (shaded portion trending toward broken line) to definitely limited availability (shaded portion trending toward solid line).

The potential for increasing water yield for each type was determined after thorough review of numerous research documents including 11 state-of-knowledge reports on watershed management recently published by the Rocky Mountain Forest and Range Experiment Station. To conserve space, reference to much of the source materials has been omitted in this report. However, a complete list of references is included in the main paper,[1] which provides greater detail on each vegetation type.

The increases are presented as the average maximum or near maximum onsite response to treatment, usually by clearcutting and type conversion. The increases for some vegetation types were then adjusted, where appropriate, to reflect the experience of some units in making adjustments for multiple use and other considerations. The increases are projected as long term averages that could be sustained indefinitely with maintenance programs. Except for the chaparral, there has been no reduction for any offsite transmission losses that might occur.

The Alpine Zone

The alpine zone is that part of the mountains above erect tree growth, which occurs at 10,000 to 12,000 feet elevation (fig. 6). Cover consists primarily of low-growing grasses, sedges, forbs, lichens, and dwarf willows. About 1.3 million

acres have been classified as alpine, virtually all of it in the Upper Basin. About 98% is National Forest land. The climate is cold, wet, and windy. Precipitation averages 40 inches or more annually, and comes mostly as snow, which is redistributed by the wind. Water yield averages 20 to 40 inches; 85% is concentrated in the May-July snowmelt period.

There is potential for increasing water yield on selected sites where evaporation of windblown snow can be reduced by trapping snow in large drifts (fig. 7). Where snow trapping is efficient, tests have shown that roughly 60 to 120 feet of fence is required to retain an extra acre-foot of water in the snow drift at the start of the melt season (Martinelli 1975). In terms of volume per unit length of fence, this amount is equivalent to 363 to 726 cubic feet per foot of fence or 44 to 88 acre-feet per mile of fence. If fences could be spaced at 500- to 1,000-foot intervals, for example, the extra water trapped would be equivalent to a uniform depth of about 4 to 17 inches over the area between fences. However, increases of this magnitude have not been demonstrated over large areas. In field application, spacing of fences could vary considerably depending on terrain, wind, and snow supply. If spacing should average 2,000 feet, the potential for increasing snow storage would be 2.2 to 4.4 inches. Even this amount should be considered tentative until results from additional research and pilot tests become available. In addition, most artificial structures are easily seen from long distances; therefore, the visual impact of such barriers should be taken into account.

Mountain Grasslands

High elevation mountain grasslands (fig. 8) and other large forest openings covered by grasses, forbs, and low-growing shrubs provide additional opportunity to increase water yield by snow management. These areas are below timberline; the reason they are treeless is not always clear. There

Figure 6.—The alpine zone in Colorado with transition to subalpine vegetation at right. The alpine zone occupies about 1.3 million acres in the Upper Basin and only about 2,000 acres in the Lower Basin.

Figure 7.—Natural drifting of snow (foreground) in the alpine can be enhanced by placing fences to put additional snow on top of an already deep snowpack. This is done to increase the runoff during summer months from such areas.

Figure 8.—High elevation (9,000-10,000 feet) mountain grasslands in eastern Arizona, where much sublimation loss occurs from windblown snow. These areas comprise about 100,000 acres in the Lower Basin and an unknown acreage in the Upper Basin.

are an estimated 100,000 acres in the Lower Basin. In the Upper Basin, these areas may be even more extensive, but the acreage is not known. In forest surveys, these areas are often included with associated noncommercial subalpine, aspen, and mixed conifer forests. Climate is similar to the associated types, although wind is usually stronger in the large openings. Precipitation averages 25 to 40 inches annually, and is mostly snow. Water yield may range from 3 inches to as much as 15 inches on the wettest sites.

The potential for increasing water yield is believed to be less than in the alpine zone because of less snow and wind. It has been estimated that streamflow from mountain grasslands in eastern Arizona could be increased by 1.5 to 2 inches if snow could be held in large drifts where it falls instead of being blown long distances across these areas (Thompson et al. 1976). Again, an important consideration is the visual impact of snow fences.

Rocky Mountain Subalpine Forests

Conifer forests, including spruce-fir, lodgepole pine, Douglas-fir, mixed conifers, and ponderosa pine, cover nearly 15 million acres within the Colorado River Basin, of which nearly 13 million acres are classified as commercial. Subalpine forests (fig. 9), composed of spruce-fir, lodgepole pine, and, for purposes of this report, Douglas-fir, occupy some 6.8 million acres in the Upper Basin; 5.5 million acres of these are considered commercial. The elevation of these forests varies from 7,000 to 11,500 feet, just below the alpine zone. The climate is cool and moist; mean temperature is near freezing. Precipitation is about two-thirds snow and averages from 20 to as much as 55 inches per year. Water yield may vary from 5 to as much as 40 inches per year, largely from snowmelt. Overall, the average precipitation is estimated at 28-30 inches and streamflow (water yield) at 12-15 inches (Leaf 1975).

The potential is good for increasing water yield in the subalpine type by managing for snow redistribution and transpiration reduction in small forest openings (Leaf 1975). Increases in water yield of from 1 to 3 inches (fig. 10) can be expected, depending on site factors and management strategies. Simulation harvest of lodgepole pine (fig. 10) was by a series of patch cuts, 5 to 8 tree heights in diameter, each covering about one-third of the planning unit. The cuts would be made at 30-year intervals spread over a planning period of 120 years with periodic thinning in the regenerated stands. The management strategy for the

Figure 9.—Subalpine forests cover approximately 6.8 million acres in the Upper Colorado River Basin. The spruce-fir type, shown in this watershed view in the Colorado Rockies, makes up about 50% of the total subalpine area.

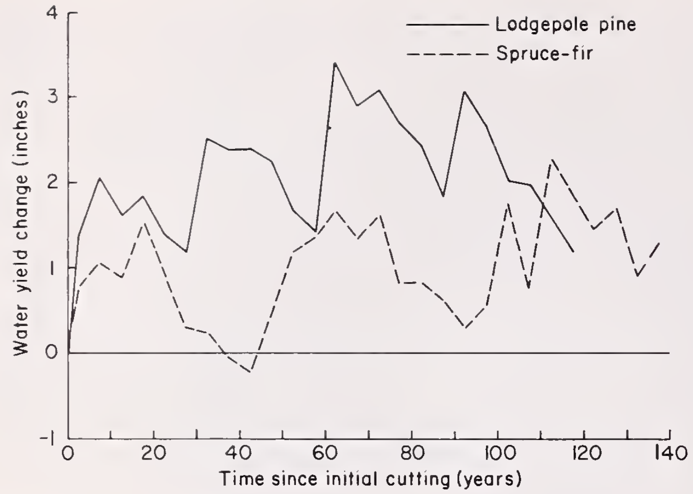

Figure 10.—Projected water yield increases from specific management strategies in lodgepole pine and spruce-fir forests (Leaf and Alexander 1975).

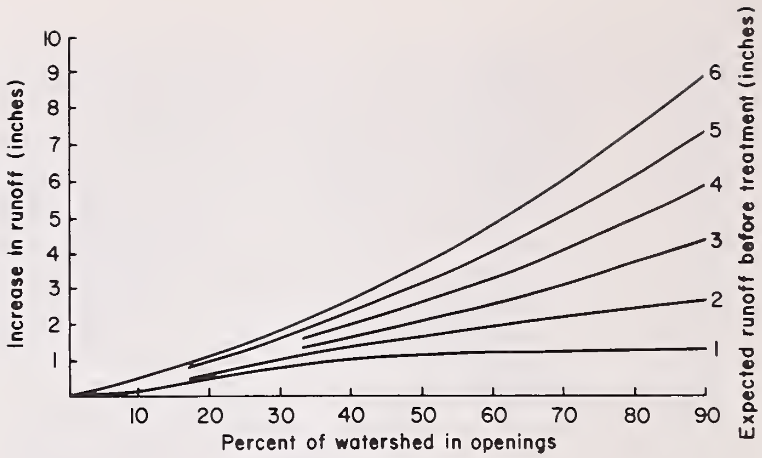

Figure 12.—Potential water yield increases from mixed conifer forests as a function of the percent of watershed in openings 3 to 8 tree heights in diameter and the expected yield without treatment (Rich and Thompson 1974).

Figure 11.—Mixed conifer forests, including Douglas-fir in the Southwest occupy about 400,000 acres in the Lower Colorado River Basin.

spruce-fir (fig. 10) was similar, except that the patch cuts would be made at 50-year intervals. In much of the Rocky Mountain area, patch cutting is considered ecologically sound if the management objective is to maintain the spruce-fir ecosystem (Alexander 1974).

Southwestern Mixed Conifer Forests

Mixed conifer forests (fig. 11) in the Southwest occupy sites that are wetter and cooler than usually occupied by pure stands of ponderosa pine and warmer, but not necessarily drier, than subalpine forest sites to the north. The most common overstory species are Douglas-fir, ponderosa pine, white fir, Engelmann spruce, aspen, southwestern white pine, blue spruce, and corkbark fir. Most of the mixed conifer stands are found between 7,000 and 10,000 feet elevation. Above 10,000 feet, mixed conifers give way to spruce-fir forests. Douglas-fir is the most important commercial timber species. For purposes of this report, all spruce-fir in the Lower Basin is included in the mixed conifer type. Together they occupy nearly 400,000 acres, mostly commercial. Precipitation averages 25 to more than 30 inches per year; one-half or more of it comes as snow. Water yield averages 3 to 5 inches, sometimes more on the wettest sites; three-fourths or more of it is from snowmelt.

Using management strategies similar to those described for subalpine forests, the potential for increasing water yield in the mixed conifer forests is estimated to be about 25% less than in the subalpine, although large clearcuts appear to give greater increases in the mixed conifer than in the subalpine. A possible explanation for this is that in

the drier, warmer climate of the mixed conifer forests, more of the response from altering the cover is attributed to reduction in transpiration and less to redistribution of snow. Increases in water yield of 3 to 4 inches are possible from clearcutting (Rich and Thompson 1974). However, without type conversion to an herbaceous cover, the increases would decline as the forest regrows. The overall estimate is 1.5 inches average increase from maintaining about one-third of the area in small openings on sites where streamflow normally averages 4 to 5 inches (fig. 12).

Rocky Mountain Aspen Forests

Quaking aspen (fig. 13) occupies approximately 3.3 million acres in the Colorado River Basin, nearly all of it in the Colorado and Utah portions of the Upper Basin. Roughly 75% is on National Forest land. The aspen type is recognized for its multiple values of wood, livestock forage, wildlife habitat, watershed protection, recreation, and esthetics. Aspen is commonly found between 7,000 and 10,000 feet elevation in clumps to extensive stands interspersed among conifers of the subalpine, mixed conifer, and cooler portions of the ponderosa pine type. Precipitation averages 20 to 40 inches, one-half or more of it snow. Water yield averages 3 to 5 inches in the Lower Basin, but may reach 20 inches in the Upper Basin.

The potential is good for increasing water yield in the aspen by type conversion, but relatively low from cutting or other practices when the objective is aspen stand regeneration. Increases up to 5 inches are possible from clearcutting aspen (DeByle 1976), but these increases decline rapidly and are gone within 10 to 15 years (fig. 14), if this prolifically sprouting species is allowed to recover the site. Therefore, if clearcutting or other removal practices were to be repeated every 80 years, as might be done for timber harvest with stand regeneration, the average annual increase over 80 years would be about one-third inch over the area actually treated. More frequent treatment has been suggested to enhance browse production for deer and elk and domestic animals (Patton and Jones 1977). If clearcutting or other methods of stand removal were practiced on a 25-year rotation, for example, increases averaging about 1 inch per year would be possible on the area actually treated.

Southwestern Ponderosa Pine Forests

Ponderosa pine (fig. 15) occupies about 1.5 million acres in the Upper Basin and about 6 million acres in the Lower Basin. About 70% is on

Figure 13.—Quaking aspen is widespread in the Colorado River Basin, with more than 90% of the 3.3 million acres located in western Colorado and eastern Utah.

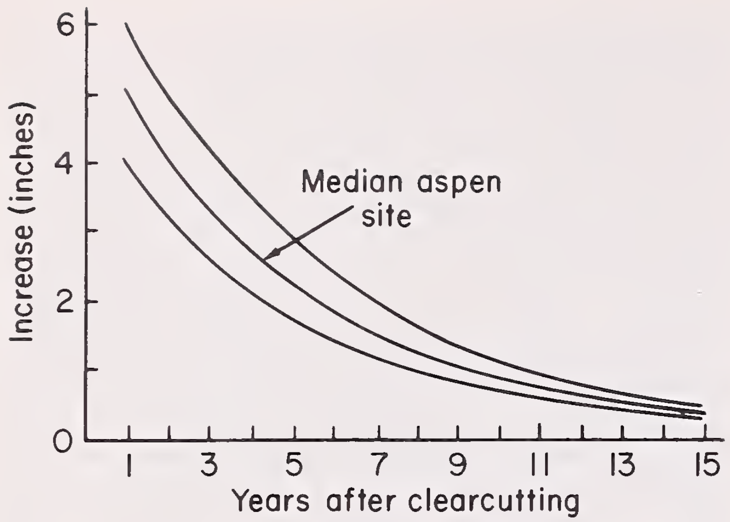

Figure 14.—Increase in water yield declines rapidly after clearcutting aspen, when regrowth is permitted (personal communication with Norbert V. DeByle, Intermountain Forest and Range Experiment Station, Forestry Sciences Laboratory, Logan, Utah).

public lands, with most of the remainder on Indian lands. Of the nearly 6.9 million acres considered capable of commercial timber production, nearly two-thirds of a million acres are in National Parks, wilderness areas, high value scenic areas, and similar land use categories. The elevation range for ponderosa pine is between 6,000 and 9,000 feet, where the type grows best on sites that are warmer and drier than those occupied by mixed conifer and subalpine forests. Gambel oak and chaparral species are common understory plants in the lower fringe area of the pine. Annual precipitation is about one-half snow and averages from 15 to 25 inches in the Upper Basin and 20 to 25 inches in the Lower Basin. Water yield is derived mostly from snowmelt and averages 2 to 6 inches annually, depending on precipitation, elevation, and soils. The overall average is probably 3 to 4 inches.

The potential for increasing water yield in ponderosa pine is less than from other commercial

Figure 15.—Ponderosa pine near Flagstaff, Ariz. after an improvement selection cut in 1941. Note thick reproduction at left. There are approximately 1.5 million acres of ponderosa pine in the Upper Basin and 6 million acres in the Lower Basin.

forest types, presumably because the pine forests are drier. Short-term increases of 1 to 3 inches may be expected from clearcutting ponderosa pine with basal area in excess of 100 square feet per acre, although these increases would not continue indefinitely without maintenance of the clearcut condition. Under a multiple use management framework, in which timber, range, wildlife, recreation, and water would all be considered in the product mix, the long-term increases of 0.1 to 1 inch are more realistic expectations (H. Brown et al. 1974). The actual amount depends on the forest cover present before treatment and the amount and method of forest reduction (fig. 16). The average increase is probably about one-half inch, unless special emphasis is placed on water production. Under a water-emphasis plan, about 1 inch might be expected where substantial reductions can be made in the forest cover by patch or strip cuts or severe thinning to a stocking level of about 40 square feet basal area per acre. Current low to intermediate stocking levels on approximately two-thirds of the ponderosa pine (Schubert 1974) (fig. 17) may preclude water increases from these areas regardless of the management emphasis, except for clearcutting.

Chaparral

The chaparral type (fig. 18) is restricted almost entirely to the Lower Basin, where it covers approximately 3.5 million acres, nearly all in Arizona. About one-half is in the National Forest system; the remainder is nearly equally divided between the Bureau of Land Management, the State of Arizona, and private and Indian ownership. Unlike the mountain brush in Colorado and Utah, the chaparral species tend to be low-growing shrubs with thick, evergreen leaves well adapted to heat and drought. The type is found most commonly on rugged terrain from 3,000 to 6,000 feet elevation. Shrub live oak is most abundant, followed by mountainmahogany. Other common shrubs are manzanita, Emory oak, silktassel, desert ceanothus, and sugar sumac.

Most species sprout prolifically from root crowns after burning or cutting; most are difficult to eradicate. Precipitation averages 20 to 22 inches overall, but ranges from as low as 16 inches in the lower fringe areas to more than 25 inches in the wettest sites. Half or more of the precipitation falls in the winter, mostly as rain. Water yield varies greatly depending on precipitation, elevation, and

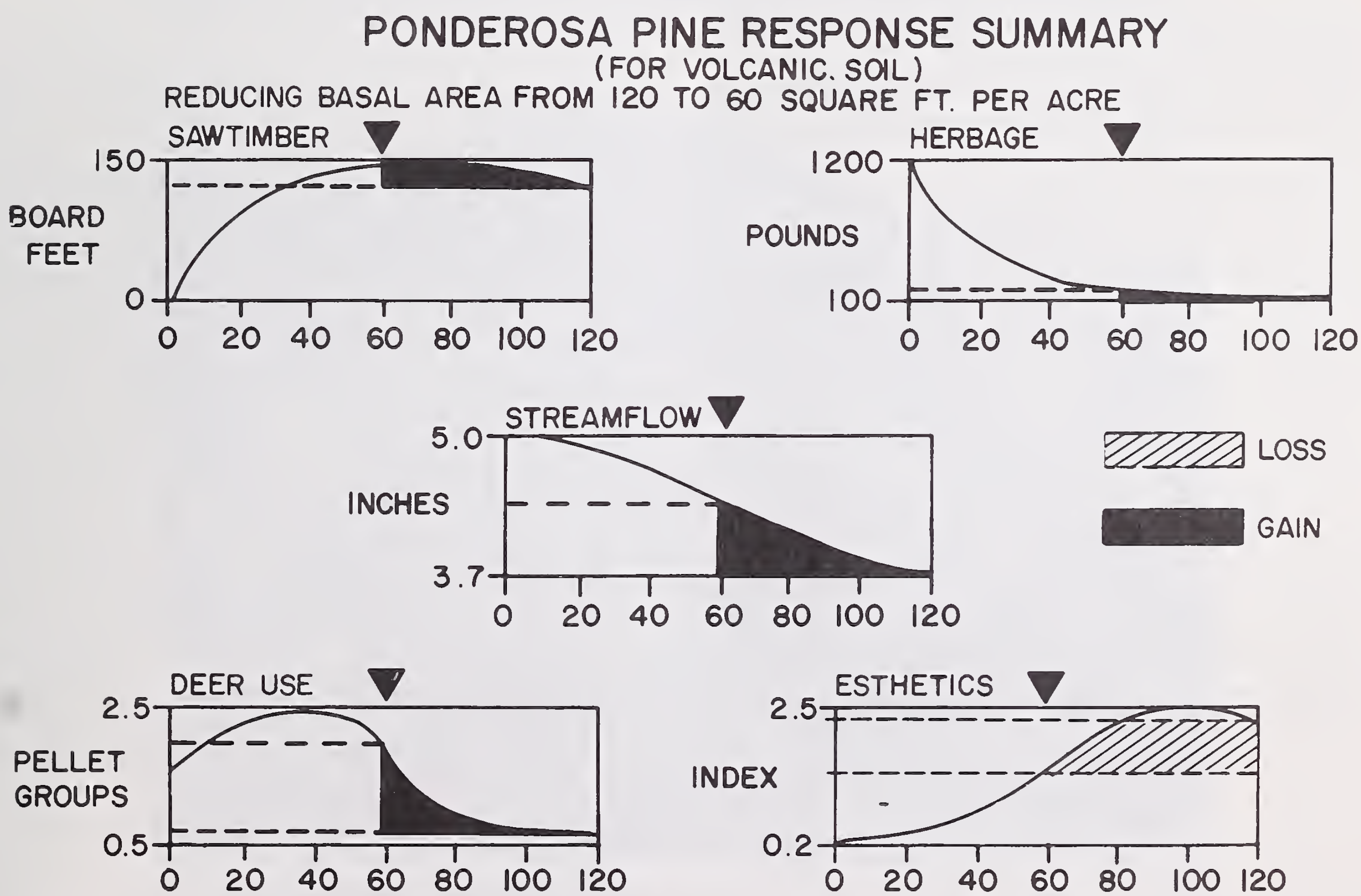

Figure 16.—Differences in resource outputs resulting from changes in timber basal area in ponderosa pine (Baker and Brown 1974).

Figure 17.—Fire has virtually eliminated ponderosa pine on this area. There are thousands of acres like this in the Southwest, that, if reforested, would likely result in less water yield than is now being produced.

Figure 18.—Chaparral covers about 3.5 million acres in the Lower Basin. This view is of 3 Bar Experimental area in central Arizona 8 years after wildfire in 1959 topkilled the dense stand of brush. The 96-acre watershed at left center was converted to grass.

soils. The overall average is 1 inch or slightly more; the lower, drier sites produce very little, while the wettest sites may yield 3 or 4 inches.

The potential for increasing streamflow by type conversion of chaparral is good on favorable sites where precipitation averages 20 inches or more (Hibbert et al. 1974). The key to increasing water yield is the replacement of deep-rooted shrubs with shallow-rooted grasses and forbs that use less water. The onsite increases determined from experimental type conversions on small watersheds range from less than 1 inch to more than 5 inches (fig. 19). The average is 3.8 inches at 22 inches precipitation. Some discounting is in order before extrapolating the research results to larger areas where conversion may not be as intensive, continuous, or as well maintained as on the experimental watersheds. Moreover, some of the increased flow may be lost to riparian vegetation downstream before it reaches storage or points of use. Therefore, the average increase expected downstream from type conversion is estimated to be about two-thirds of the onsite increase, or 2.4 inches where precipitation is 22 inches (considered average for treatable chaparral). Other considerations will limit the amount of type conversion to a fraction of the total acreage.

Of the 1.8 million acres of chaparral on National Forest lands, more than 200,000 acres are in wilderness and other special use areas, where conversion is not compatible with present land use policy. A much larger portion, nearly 40% of the remaining chaparral, is considered too dry and open (crown cover less than 30%) to be a good risk for water yield improvement. Also, much of the chaparral is on excessively steep slopes. In a study of chaparral conversion potential on National Forest lands in the Salt-Verde Basin above Phoenix, Ariz. (T. Brown et al. 1974), about 10% of otherwise treatable chaparral was on slopes steeper than 60%, which was the upper limit considered safe for conversion. However, some land managers feel that the 60% slope criterion is too steep for practical field application, and that the upper limit should be 50%, or even 40%. Since approximately 40% of the chaparral is on slopes between 40% and 60%, the steepness at which conversion can be safely accomplished is extremely important. Approximately 20% less area would be available for conversion if the maximum operable slope is lowered from 60% to 50%, and another 20% of acreage would be lost between 50% and 40% slope. Also, substantial acreages may be excluded for treatment, or given low priority, because of operational restrictions or geographic location, such as chaparral on slopes of isolated mountain ranges, where an increase in water

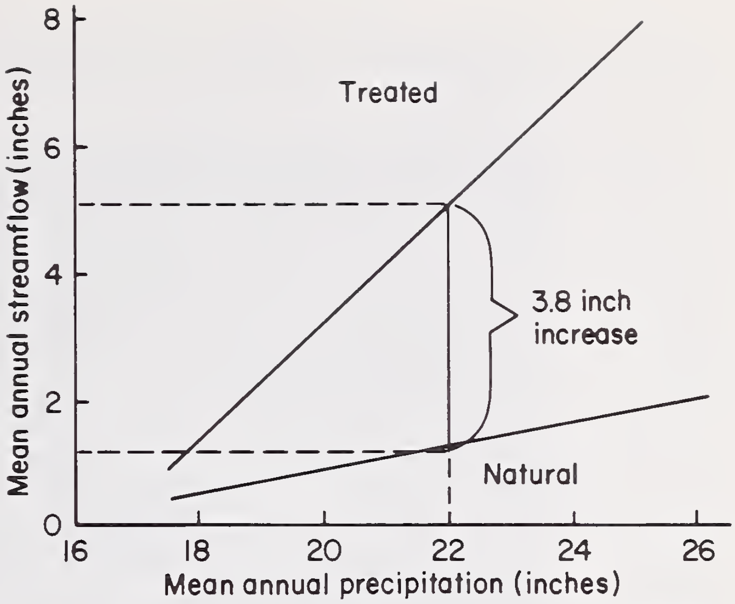

Figure 19.—Average water yield from natural and converted chaparral is a function of precipitation. Difference between lines is attributed to treatment (Hibbert et al. 1975).

would be of questionable value. Therefore, both the 1 acre in 5 estimate for treatable chaparral and the 2.4-inch water yield increase projection probably would be considered the most optimistic potentials attainable by large-scale management efforts in the chaparral.

Further, use of the arithmetic average to describe annual water yield potential can be misleading, because this value (2.4 inches in this case) will not be equalled or exceeded 50% of the years as would occur if precipitation and runoff were normally distributed. In the chaparral of central Arizona, precipitation is less than average about 58% of the years. Since runoff increases exponentially with precipitation, yearly runoff amounts are skewed ever farther to the dry side of the distribution curve. Wet years tend to yield many times as much water as dry ones. Thus, even though precipitation exceeds the mean in only about 4 years in 10, more than 80% of the water yield increases are produced in these wetter than average years. Storage facilities are imperative to get full benefit of increased water yields in wet years. To the extent that downstream storage capacity is exceeded (which happened 7 times in the past 50 years in the Salt-Verde Basin above Phoenix) and water is spilled, runoff increases from conversion would be lost to the full extent of the release, assuming no further beneficial use could be made of the water downstream.

Mountain Brush

Mountain brushlands (fig. 20) are extensive only in the Upper Basin, where they are found on about

3.3 million acres. Less than one-third of the area is under National Forest administration. The Bureau of Land Management administers much of the remainder, with undetermined acreages in state, private, and Indian ownership. Gambel oak, mostly in brush form, growing 2 to 12 feet high in clumps or thickets, is the predominant species. Associated shrubs, which sometimes dominate the site, are chokecherry, serviceberry, snowberry, big sagebrush, mountainmahogany, and other woody species. Though sometimes classified as chaparral, and similar in appearance, the mountain brush type differs in that most of the species are deciduous; thus they are active only in the summer. The type is commonly found at 5,000 to 10,000 feet elevation on relatively warm, dry exposures. Average annual precipitation ranges from 16 to 24 inches, less than one-half falling as snow. Water yield of 1 to 6 inches can be expected.

There has not been sufficient research in the mountain brush to accurately predict how treatment will affect water yield. However, results from plot studies in Utah (Johnston et al. 1969) suggest that response to brush conversion may be less than in the chaparral. A rough estimate is 1 to 3 inches of additional water from type conversion. If shrub regrowth is not controlled, the increase will be short-lived, probably about 3 to 5 years. It is difficult to estimate the amount of mountain brush that would or could eventually be converted to grass, in view of other resource values and social and economic factors that should be considered in resource management decisions.

Big Sagebrush

Big sagebrush (fig. 21) is found on some 26 million acres in the Colorado River drainage area, mostly on lands administered by the Bureau of Land Management. Only a small percentage of the 18 million acres in the Upper Basin, and none in the Lower Basin are considered as having potential for increasing water yield. Big sagebrush thrives over a broad range in elevation and climate. It is found at elevations up to 10,000 feet, and is well adapted to warm, dry growing seasons at lower elevations. Precipitation varies from 8 to 20 inches; only the wettest sites have potential for water yield improvement by vegetation manipulation. Water yield is less than 1 inch on most sagebrush lands. However, where precipitation exceeds 14 inches, yield may be greater; it can reach 3 to 4 inches on the wettest sites. The relocation of snow by winter winds and the resulting water loss by sublimation are important features of this type.

The potential for increasing water yield in big sagebrush is poorly defined, although type conversion on the most favorable sites might increase yield by 15%, or up to one-half inch (Sturges 1975).

Figure 20.—Mountain brush (mostly Gambel oak, as in this photo) covers some 3.3 million acres of mountain lands in the Upper Basin.

Figure 21.—Big sagebrush covers vast areas in the Upper Basin. However, there is potential for increasing water yield only on the most favorable sites by management of the vegetation and snow.

Figure 22.—By trapping snow behind snow fences such as this evaporation of blowing snow is reduced, and snowmelt water is concentrated to enhance its delivery to the stream or ground water recharge.

Additional increases of 1 inch or more may be possible by trapping blowing snow behind snow fences (fig. 22) in areas where the winter snow water equivalent is at least 8 inches (Tabler 1975).

Pinyon-Juniper

The pinyon-juniper ecosystem is the most extensive forest type in the Colorado River Basin, occupying some 32 million acres. Pinyon-juniper lands are mostly under federal administration: roughly 32% Bureau of Land Management, 20% USDA Forest Service, 19% Indian trust, and 29% other, including state and private holdings. Principal species are Utah, Rocky Mountain, one-seed, and alligator junipers, and Colorado and single leaf pinyon pines. The type is most commonly encountered in the foothills, low mountains, and low plateaus between 4,000 and 7,500 feet elevation. Though normally considered low in commercial value, the pinyon-juniper type has been and still is an important source of forage for livestock, food and cover for wildlife, and various products such as fence posts, firewood, pinyon nuts, and Christmas trees. Extensive pinyon-juniper control programs have been conducted in the Southwest (fig. 23).

Precipitation averages 12 to 18 inches, with local areas receiving up to 20 inches. Summer rains account for half or more of the precipitation in the Lower Basin, while winter rains and snow provide the bulk of the moisture in the Upper Basin. Water yield is generally less than 1 inch, although some of the better watered sites may approach 3 inches.

The potential for increasing water yield in the pinyon-juniper type is negligible on most sites, although small increases (less than 0.5 inch) may be possible by type conversion on the wettest sites (Clary et al. 1974). Overall, the potential should be considered poor.

Upstream Riparian Areas

Upstream riparian areas (fig. 24) consist of riparian vegetation along relatively small streams that drain to the Colorado River and its major

Figure 23.—Pinyon-juniper conversion remains controversial (Lanner 1977); however, when treated areas are kept small and fitted to the natural landscape, the visual impact is greatly reduced, wildlife habitat is improved, and forage production is increased (Hurst 1976). Water yield is little affected by conversion.

tributaries. Of particular interest are streams that emerge from the mountains and flow across hot, dry lowlands to reach major streams and reservoirs. Total area occupied by these bands of vegetation exceeds 100,000 acres, the estimate for the Lower Basin alone. No acreage figure is available for the Upper Basin. Common riparian trees and shrubs are cottonwood, willows, saltcedar, arrowweed, saltbushes, mesquite, sycamore, and alders. Elevations range from about 1,000 feet to over 7,500 feet. Estimates of potential evapotranspiration for the lowest elevations are as high as 6 feet per year. The upstream riparian areas are of special interest because they are (1) areas of heavy water consumption, (2) conveyance systems for water yield increases generated on upstream watersheds, (3) areas of high potential for saving water by eradication of trees and shrubs, and (4) areas of high scenic value and high value for wildlife and recreation.

The potential for increasing water yield in the upstream riparian areas can be greater per unit area than for any other vegetation type. Water savings of from 6 to 24 inches appear possible when riparian vegetation is eradicated along permanently flowing streams (Horton and Campbell 1974). However, extensive removal of trees and shrubs from these areas could impair scenic and recreation values, adversely affect channel stability, and destroy some of the most productive wildlife habitat in the Southwest. Less than complete removal of trees and shrubs would correspondingly reduce the water savings potential. Thus it appears unlikely that upstream riparian areas can be counted on for significant augmentation of the water supply.

Summary of Potential Increases and Comparison with Earlier Estimates

The potentials for increasing water yield in 11 cover types are summarized in tables 1 and 2 for the Upper and Lower Basins. The data are presented as ranges of average onsite increases in area inches

Figure 24.—Upstream riparian vegetation, primarily alders and sycamores at 5,000 feet, along Tonto Creek in central Arizona. Water use by this streamside vegetation is high in summer and low in winter, when this photo was taken.

Table 1.—Potential and adjusted water yield increases (inches) and total area of each vegetation type, Upper Colorado River Basin.

	Millions of acres	Potential increase	Adjusted[1] increase
Alpine	1.3	2 - 5	
Mountain grasslands	unknown	1.5 - 3	
Subalpine	6.8	1 - 3	[2]1 - 3
Aspen	3.2	3 - 5	0.3 - 1
Ponderosa pine	1.5	1 - 3	.1 - 1
Mountain brush	3.3	1 - 3	
Big sagebrush	17.6	0 - 1	
Pinyon-juniper	12.6	0 - 0.5	
Upstream riparian	unknown	6 - 24	

[1]*Adjustments reflect multiple use and other considerations.*

[2]*No reduction was indicated for subalpine forests because patch cutting, which tends to be most water productive, was also considered to be acceptable from multiple use and silvicultural standpoints. Under shelterwood, individual tree selection, or group selection harvest methods, water yield increases probably would be less than one-half these values.*

Table 2.—Potential and adjusted water yield increases (inches) and total area of each vegetation type, Lower Colorado River Basin

	Millions of acres	Potential increase	Adjusted[1] increase
Mountain grasslands	0.1	1.5 - 2	
Mixed conifer	.4	3 - 4	1 - 2
Aspen	.1	3 - 5	0.3 - 1
Pondersoa pine	6.0	1 - 3	1 - 1
Chaparral	3.5	1 - 5	2.4
Pinyon-juniper	19.9	0 - 0.5	
Upstream riparian	.1	6 - 24	

[1]*Adjustments reflect multiple use and other considerations.*

(water uniformly distributed over the treatment area) expected from manipulation of vegetation and snow. In commercial conifer forests—subalpine, mixed conifer, and ponderosa pine—treatment area refers to the entire working area where timber harvesting or other management practices are applied, including intervening trees, shrubs, or open areas which may receive some type of silvicultural treatment, or are left undisturbed. However, in the aspen, brushlands, pinyon-juniper, and upstream riparian zones, treatment area refers only to area cleared, converted, or otherwise modified; it does not include surrounding or intervening areas left untreated for wildlife, esthetics, or other purposes. A somewhat different interpretation of treatment area is applied to alpine, mountain grasslands, and high elevation sagebrush lands, where snow management is the water yield improvement method. Under these situations, treatment area refers to the snow source area (fetch) upwind of snow fences or other barriers, plus the downwind accumulation area where the snowdrift forms.

Variations in site capability, climate, and treatment methods determine the range of response in each of the vegetation types. The greatest response in streamflow can be expected on sites where large reductions can be made in evapotranspiration, whether this is done by trapping snow or by reducing vegetation. Clearcutting and type conversion are the methods that usually increase streamflow the most, except in the subalpine zone, where patch cutting is considered most water productive.

The vegetation type that offers the best opportunity for improving water yield in the Upper Basin is the subalpine, followed by aspen, mountain brush, and ponderosa pine. In the Lower Basin, the opportunity to improve the water supply is best in chaparral and ponderosa pine. Opportunities in mixed conifer and aspen are limited by the small acreage of these forests.

The potential for increasing water yield per unit area of treatment is greatest in upstream riparian vegetation, and is least in pinyon-juniper and sagebrush lands. However, the upstream riparian

areas are not likely to be the source of large amounts of additional water because the area is small and values are high for other uses that, for the most part, are not compatible with treatment practices required to accentuate water yield. Although big sagebrush and pinyon-juniper are extensive types, neither shows promise for improving water yield, except on the most favorable sites. While the potential appears greater in the alpine and mountain grasslands, the increases (tables 1 and 2) must be considered tentative, since they are based on increased catch of snow by snow fences on experimental sites. It has not been tried within an actual watershed.

Where clearcutting and type conversion are not acceptable, water yield response will be less than full potential, depending on the amount and methods of vegetation reduction. The potential increases for the mixed conifer, ponderosa pine, aspen, and chaparral vegetation types were adjusted for multiple use and other considerations (tables 1 and 2 and parentheses in table 3). The potential increases were reduced by one-half or more in all the commercial forest types, except the subalpine forests, where patch cutting, which tends to be most water productive, was also considered to be acceptable from a multiple use standpoint. Where patch cutting is not acceptable in subalpine forests, and other silvicultural systems, such as individual tree selection, group selection, or shelterwood methods, are used, the potential for increasing water yield may be less than one-half that expected from patch cutting (Leaf 1975).

Adjustments for mixed conifer forests reduced the potential increases from a depth of 3 to 4 inches to a depth of 1 to 2 inches over the area being managed, based on an assumed management strategy of periodic patch cutting to maintain about one-third of the area in small openings. In ponderosa pine, clearing away dense stands of trees can increase water yield by 1 to 3 inches over the areas cleared. However, management practices designed to provide an acceptable mix of forest products and other resources are expected to produce, on the average, only about 0.1 to 1 inch of additional water per year. The adjustments for aspen from 3 to 5 inches down to 0.3 to 1 inch reflects a somewhat arbitrary choice of clearcutting options, one at rotation age of 80 years for wood products (0.3 inch average annual increase for 80 years on the area actually clearcut) and the other at rotation age of 25 years to favor wildlife (1.0 inch average annual increase for 25 years on the clearcut portions). The adjustment in the potential increase for chaparral vegetation from 1 to 5 inches to an average of 2.4 inches for areas actually converted reflects lower onsite efficiency expected from a mosaic pattern of treated and untreated areas, and an estimate of offsite losses in transit to points of use downstream.

Water yield potentials for selected vegetation types are compared in table 3 with two previous evaluations in 1960 and 1974. The 1960 Senate Select Committee estimates pertain to the Southwest generally and the 1974 Ffolliott-Thorud estimates to the State of Arizona only. Current unadjusted estimates compare fairly well with the Senate Committee estimates in the subalpine, mixed conifer, aspen, and pinyon-juniper types, but are considerably higher in ponderosa pine and chaparral. However, the Senate Committee value of 0.5 inch of increased water yield for the ponderosa pine agrees with the current adjusted estimate of 0.1 to 1.0 inch. The higher projection for the chaparral in the current evaluation can be attributed to the favorable outcome of several brush conversion studies of the Arizona Watershed Program[6] conducted after the Senate Committee report in 1960. Similar tests in the pinyon-juniper vegetation failed to strengthen early projections for low increases from type conversion in this extensive cover type.

[6]*A cooperative research effort by federal, state, and water user interests was started in the 1950's to investigate the feasibility of increasing water yield in Arizona by manipulation of vegetation.*

Table 3.—Comparison of current evaluation of potential increases (inches) with other estimates

	Current evaluation	U.S. Senate 1960	Ffolliott & Thorud 1974 (Arizona only) Low option	High option
Subalpine	1 - 3	3.0		
Mixed conifer	[1]3 - 4 (1 - 2)	4.5	1.2	6.0
Chaparral	1 - 5 (2.4)	0.5	1.2	2.4
Ponderosa pine	1 - 3 (0.1 - 1)	.5	1.2	2.4
Aspen	3 - 5 (.3 - 1)	3.0	included with mixed conifer	
Pinyon-juniper	0 - 0.5	.25	negligible	

[1]*Figures in parentheses are adjusted to reflect multiple use or other considerations.*

The 1974 estimates by Ffolliott and Thorud are based on low and high treatment options in three vegetation types. Treatment in the mixed conifer forests would convert to grass one-third to two-thirds of the area next to stream channels. The low option projection of 1.2 inches of increased water yield from converting one-third of the area appears consistent with the current estimate of 3 to 4 inches from complete conversion, since response in this vegetation type appears proportional to area treated. However, the high option projection of 6 inches from converting only two-thirds of the forest appears overly optimistic. Treatment options in the chaparral would convert 40% and 60% of the area to grass for increases of 1.2 and 2.4 inches. These projections fall within the range of current estimates of 1 to 5 inches for an area fully treated (the average on favorable sites is 3.8 inches adjusted to 2.4 inches for onsite and offsite losses).

In ponderosa pine, the low option would clear one-third in strip cuts for 1.2 inches increase, and the high option would clear two-thirds in strip cuts for 2.4 inches increase. These are slightly higher estimates but not necessarily incompatible with current unadjusted estimates. However, since the current adjusted estimate of 0.1 to 1 inch is considered more realistic from a management standpoint, the water yield potential in ponderosa pine is believed to be much less than estimated for the Lower Basin by the Ffolliott-Thorud study. Further, the acreages considered suitable for treatment in the Ffolliott-Thorud study may not be available, since much of the ponderosa pine is in poorly stocked condition.

Assessment

Amount of Additional Water

The amount of additional water that can be produced within a multiple use management concept needs to be determined. It can be theorized that the maximum increase possible could be estimated by multiplying total acreage times the unadjusted average increase for each vegetation type (tables 1 and 2). If this were done in this study, some 4 million acre-feet would be indicated for the Upper Basin and about 2 million acre-feet for the Lower Basin.

However, this type of estimate ignores several basic problems that cause actual yield increases to fall short of the maximum potential.

1. Only a portion of each vegetation type could be treated economically for water yield increases. The amount depends on the demand for water and its value in the market place.
2. Consideration of other resource values and desires of the public tend to reduce both the area that can be treated and the effectiveness of treatments below that which could be obtained if water yield was the main objective of management.
3. The time frame required for water yield improvement practices to become fully operational is probably in the order of several decades for commercial forests with timber harvest rotation ages of up to 120 years. However, less time would be required for noncommercial types, such as chaparral.

Thus, the amount of water that can be produced by vegetation management can best be quantified in terms of a range of alternative management options that would include consideration of all factors above.

Another approach to assessing water yield potential is to determine how much treatment would be required to meet certain water augmentation goals. For example, the proposed Yuma Desalting Plant[7] on the lower Colorado River will produce up to 42,000 acre-feet per year of highly concentrated reject water, which would not be suitable for agricultural, municipal, or industrial uses. The Lower Basin states are unwilling to lose any water through a desalting plant reject stream because of anticipated future shortages. Therefore, the need arises to augment the existing supply by 42,000 acre-feet to make up the difference. Although vegetation management may not be the appropriate way to get the extra water, it is used here as an example to illustrate the role that vegetation management could play in augmentation of the surface water supply.

The 42,000 acre-feet could be obtained by placing 250,000 acres of subalpine forests in the Upper Basin under management designed for water yield improvement as a major objective. Or, the 42,000 acre-feet could be obtained by converting 210,000 acres of brush to grass in the Lower Basin. Larger acreages in each case might need to be treated, if water yield improvement practices should require modification to adequately accommodate other resource values.

As a second example, suppose it became necessary to augment the water supply of the Colorado River by 750,000 acre-feet per year on the average, with no restriction on where in the basin the water should be generated. Since the Upper Basin yields

[7]*Reject stream replacement study status report, January 1978, 102 p. USDI Bureau of Reclamation, Lower Colorado Region, Boulder City, Nevada.*

nearly five times as much water as the Lower Basin, it would be consistent to look to the Upper Basin for most of the extra water, say 500,000 acre-feet (3.5% increase), and to the Lower Basin for 250,000 acre-feet (8% increase).

In the Upper Basin, treatments as described earlier might be considered on the acreages indicated in table 4. The average increases projected for each vegetation type are arithmetic averages of the ranges in values shown in tables 1 and 2. Averages of the adjusted values were used for the aspen, mixed conifer, ponderosa pine, and chaparral types. In the Lower Basin (table 5), a larger percentage of the area would have to be treated to get the increases desired.

From these arbitrary examples of hypothetical treatments and acreages, it appears that 500,000 acre-feet of extra water could be generated in the Upper Basin by committing up to 22% of each vegetation type, except the aspen forests, in which 40% would be treated. The management strategy for the aspen type is 80-year rotation clearcut harvest in patches covering 20% of the total area plus 25-year rotation of patch cuts on an additional 20% of the total area.

Treatment on 22% of the subalpine forests including Douglas-fir, would produce 50% of the total increase. Mountain brush and aspen would be the next largest contributors. The increases attributed to the alpine zone and big sagebrush vegetation are projected with less certainty than for the other types because it is uncertain that these amounts of water can be generated on a watershed basis.

In the Lower Basin, more extensive treatments would be required to generate 250,000 acre-feet of extra water. Only small increases could be expected from snow management in the mountain grasslands and from patch cutting in the aspen, even if these cover types were fully treated. Also, because of the limited acreage of the mixed conifers, the potential for this type is small. Therefore, attention is focused on the chaparral and ponderosa pine forests, where 92% of the expected increase would be generated by treating about 20% of the chaparral and 33% of the ponderosa pine. Again, these acreages may not produce the desired amount of extra water if the suggested treatment practices should require modification to better accommodate other resource values.

Why not treat a larger percentage of chaparral, since the potential is good for increasing yield and the type is low in commercial value? First, large portions may not be treatable because cover is too sparse or slopes too steep, or because certain areas are classified for other uses such as wilderness. Also, the term treatment area as used for the chaparral refers to the actual area converted to grass or otherwise modified; it does not include surrounding or intervening areas left untreated for wildlife or other purposes. Therefore, treatment of 20% of the chaparral or mountain brush involves a much larger all-inclusive acreage than one in five, since untreated intervening areas may equal or exceed the acreage actually converted to grass.

However, availability of treatable acres is uncertain in all of the vegetation types. The arbitrary selection of treatable acreages used in this assessment should not be construed to mean that these acreages would be available for treatment. Treatable acreages may ultimately prove to be less (or more) than these, in which case the projected increases in water yield would also be different.

Cost of Producing Additional Water

Costs of initial treatment vary from a few dollars per acre to a few hundred dollars per acre, depending on the type of treatment and type of vegetation. Initial treatment cost figures are of limited value, however, in determining cost of increased water yield, unless tradeoffs are included and maintenance costs are properly evaluated over a period of years. Some of the treatment possibilities in the example given here may not now be economically feasible, although they might be at some later date.

Although few good economic evaluations are available, cost estimates indicate where low- and high-cost water could most likely be obtained. Generally, water derived from management of commercial forests is the least expensive, since relatively small additional outlays or tradeoffs are required to get the extra water. Several estimates made during the mid to late 1960's pegged costs of additional water from multiple use management of western forests at $1 to $5 per acre-foot. Estimates of costs of increasing water yield by type conversion in the chaparral ranged from $10 to $50 per acre-foot, the average being near $20. The cost of producing extra water by snow fences in alpine and mountain grassland areas has not been determined. However, some preliminary estimates[8] indicate that, on favorable sites, additional water might be obtained at costs of $10 to $20 per acre-foot. These costs would be higher today, although the relationship of cost to value of water may not have changed much.

In an economic analysis of chaparral conversion in central Arizona, T. Brown et al. (1974) con-

[8]*Martinelli, M., R. Tabler, and R. A. Schmidt. 1975. An estimate of snow management potential on Straight Canyon barometer watershed, Utah. 9 p., unpublished report. USDA For. Serv., Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.*

Table 4.—Hypothetical treatments and percentage of areas necessary to increase water yield in the Upper Basin by 500,000 acre-feet per year

	Millions of acres	Percent treated	Method of treatment	Average[1] increase	Increased yield
				(*inches*)	(*acre-feet*)
Alpine	1.3	5	Snow fences at 2,000 feet average spacing	3.50	19,000
Subalpine	6.8	22	Maintain ⅓ area in small patch cuts	2.00	249,000
Aspen	3.2	20	80-year rotation clearcuts with regeneration	0.33	18,000
		20	25-year rotation clearcuts with regeneration	1.00	53,000
Ponderosa pine	1.5	20	Reduce to and maintain 60-80 ft^2 basal area per acre by patch cuts, strip cuts, thinning	.55	14,000
Mountain brush	3.3	20	Type conversion to grass	2.00	110,000
Big sagebrush	17.6	5	Type conversion to grass combined with snow fences	.50	37,000
Total					500,000

[1]*Arithmetic average of adjusted or potential increases shown in table 1, except the aspen, which is explained in the section on aspen.*

Table 5.—Hypothetical treatments and percentage of areas necessary to increase water yield in the Lower Basin by 250,000 acre-feet

	Millions of acres	Percent treated	Method of treatment	Average[1] increase	Increased yield
				(*inches*)	(*acre-feet*)
Mountain grasslands	0.1	10	Snow fences at 2,000 feet average spacing	1.75	1,500
Mixed conifer	.4	33	Maintain ⅓ area in small patch cuts	1.50	16,000
Aspen	.1	20	80-year rotation clearcuts with regeneration	0.33	500
		20	25-year rotation clearcuts with regeneration	1.00	1,500
Ponderosa pine	6.0	33	Reduce to and maintain 60-80 ft^2 basal area per acre by patch cuts, strip cuts, thinning	.55	91,000
Chaparral	3.5	20	Type conversion to grass	2.40	140,000
Total					251,000

[1]*Arithmetic average of adjusted or potential increases shown in table 2, except the aspen and chaparral, which are explained the sections on aspen and chaparral.*

sidered costs and benefits of converting 850,000 acres of chaparral to grass. Annual benefits from the most favorable alternative were found to be (1) 0.21 acre-foot of increased water yield per acre of converted chaparral delivered downstream and valued at $12.50 per acre foot, (2) 0.24 additional animal-unit-month (AUM) per acre of grazing capacity valued at $6.51 per AUM, and (3) $0.34 per acre reduction in firefighting costs. The average per-acre annuity benefit ($4.49) minus the annuity cost ($1.98) left a net average annual return of $2.51 per converted acre (1972 prices).

While increased forage and reduced firefighting costs helped to defray cost of conversion and maintenance, the value of the increased water satisfied more than one-half of the total cost. Although the relative inputs from increased forage and reduced firefighting costs varied between areas, it seems reasonable to assume that in areas with a benefit-cost ratio greater than 1, additional water would be produced for less than its valuation of $12.50 per acre-foot.

The value of additional water is difficult to determine because of the complicated nature of water rights and laws governing water use and distribution in the Colorado River Basin. Seldom do economic principles operate freely to determine the price of water. In the above described economic analysis (T. Brown et al. 1974), the average value of additional water delivered to the Salt River Valley was estimated at $12.50 per acre-foot, including hydroelectric power revenues from water falling through the series of dams in the Salt River above Phoenix. The value of the additional water was based on the assumption that the primary user of any additional water in the Valley, at least to the year 2000, would be the agricultural sector—there being some unmet demand for water to irrigate low-valued feed grain and forage crops. All other, higher valued demands are already met. The marginal value of water (that is, the most the farmer could pay for additional water and still pay variable costs) was estimated at $11.20 per acre-foot (1972 prices) (O'Connell 1972, T. Brown et al. 1974).

The value of water may increase relative to other values and costs in the future as ground water depletes and demand for water increases as a result of anticipated population growth and energy development within the Colorado River Basin. In anticipation of future water shortages, the Central Arizona Project (scheduled for completion in the mid-1980's) will deliver Colorado River water to central and southern Arizona at a charge of at least $46[9] per acre-foot for municipal-industrial users. Since this price reflects willingness to pay, it is suggested that additional water from vegetation management may be equally valuable in certain areas.

Time Frame for Implementing Water Yield Improvement Practices

Long-range planning would be required to fully implement water yield improvement practices outlined in this report. In slow-growing forests of the subalpine zone, harvest rotations are of the order of 120 years, although full water yield potential could be realized sooner than the rotation age of forest trees. However, demand for wood products, physical limitations, and economic constraints, among others, will prevent rapid implementation of water improvement programs. For example, demand for aspen wood products is much too low for an annual harvest of aspen to sustain the water yield potentials projected in tables 4 and 5. Demand for aspen products is expected to increase (Wengert 1976), but the time frame is 25 to 40 years.

Some water yield improvement practices could be implemented within a few years; however, that would result in immediate augmentation of water supplies. Type conversion of brushlands to grass is the most promising approach for the Lower Basin, where the potential in the chaparral has been well researched, and is now in the pilot testing phase. Studies are needed in the Upper Basin to determine extent and applicability of similar treatments for the mountain brushlands.

Other Considerations

Many uses of the forest are compatible with efforts to increase water yield (fig. 16). Reducing forest cover also improves herbage production and can significantly reduce fire hazard in certain situations. Treatment may be beneficial for some species of wildlife and detrimental for others (Franzreb 1977). While scenic beauty usually suffers following treatment, the site tends to recover

[9]In 1974, the Central Arizona Water Conservation District Board set tentative canal side charges for CAP water to M&I users at $32.50 per acre-foot plus $13.50 per acre-foot to cover operation, maintenance, and repair costs (for agricultural users these charges are respectively, $2.00 and $13.50). These charges can be expected to increase with inflation and other causes. Barr and Pingry (1977) estimated the required canal side charge to M&I users in 1976 dollars at $51 per acre-foot and the full economic cost at more than $100 per acre-foot, including operation, maintenance, repair, distribution, and treatment costs.

toward (and may even exceed) previous esthetic levels (Daniel and Boster 1976). Further, some forest types, such as aspen, may best be regenerated by clearcutting, or some other form of stand reduction, that will promote development of vigorous new stands.

Although streamflow has been shown to increase as a result of treatment on numerous small experimental watersheds, there is no assurance that the water yield increases projected here can be physically demonstrated at downstream reservoirs or points of use even if transmission losses are negligible, since the increased flows may not be detectable by conventional measurement techniques after combining with flows from other sources (Bethlahmy 1974). The amount of water yield increase resulting from treatment must be taken on faith unless special gaging and statistical controls are implemented to verify the increases. Pilot demonstrations on watersheds of several thousand acres would help to verify the increases, and bridge the gap between the small experimental watershed and large-scale water yield improvement projects.

Weather modification to increase winter snowpack is also being considered as a means of augmenting the flow of the Colorado River. Atmospheric scientists involved in weather modification generally agree that snowfall can be increased in mountainous regions by 5% to 30%, with 10% an average prediction based on current technology.[10] The combined effects of weather modification and vegetation modification on the same area produce a synergistic interaction that increases streamflow more than if the two practices are applied separately. In essence, vegetation treatments become more efficient as precipitation increases. Assuming a 10% increase in winter precipitation from weather modification, the increased efficiency of vegetation management is expected to be in the range of 5% to 10%. Thus, there is justification for combining the practices, when possible.

[10]*PSIAC Water Management Subcommittee. Herbert B. Osborn, chairman of task force report: "State-of-the-art in weather modification in the Pacific Southwest." April 1977. 10 p.*

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Water yield from forest and rangelands can be augmented by managing vegetation and snow to reduce evapotranspiration. Some arbitrary goals to increase water yield were chosen to illustrate the potential for increasing water yield, and treatments were hypothesized to get these increases.

Keywords: Watershed management, snow management, land use, forest land, brushlands, surface waters, runoff, watersheds.

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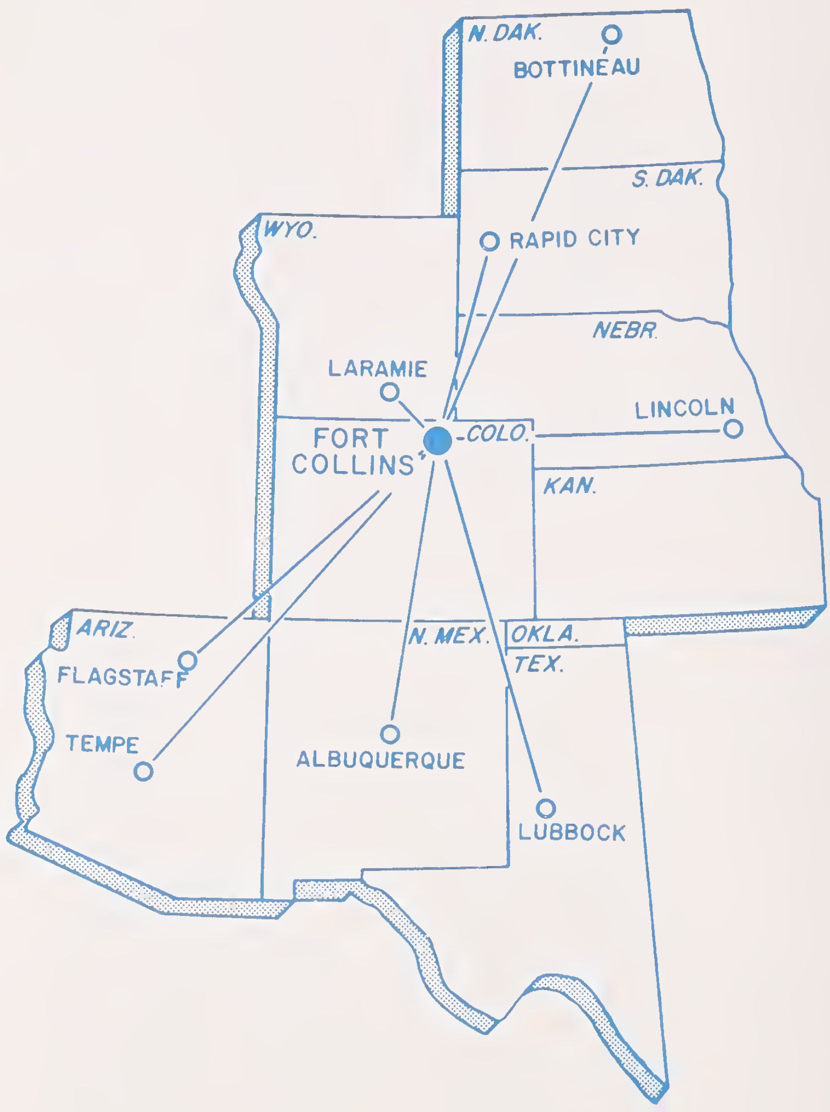
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